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CONVENTION

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Patents Act 1990

REQUEST FOR A STANDARD PATENT

AND NOTICE OF ENTITLEMENT

The Applicant identified below requests the grant of a patent to the nominated person identified below for an invention described in the accompanying standard complete patent specification.

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[54]Invention Title:

AN OPTICAL FIBER TELECOMMUNICATIONS METHOD, A LINK USING THE METHOD, AND A PUMPING SYSTEM FOR FOUR-WAVE MIXING IN PARTICULAR FOR THE LINK

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[31,33,32]

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Applicant states the following:

1. The nominated person is the assignee of the actual inventor~~(s)~~

2. The nominated person is
   - the applicant
   - ~~the assignee of the applicant~~
   - ~~authorised to make this application by the applicant~~

   of the basic application.

3. The basic application~~(s)~~ was/~~were~~ the first made in a convention country in respect of the invention.

The nominated person is not an opponent or eligible person described in Section 33-36 of the Act.

8 November 1994

Alcatel N.V.
By PHILLIPS ORMONDE & FITZPATRICK
Patent Attorneys
By

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David B Fitzpatrick

Our Ref : 388880

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Light waves carrying a signal to be transmitted are guided along a line made up of optical fibers having chromatic dispersion. To compensate for the effects of the dispersion, a four-wave mixing phenomenon is caused at at least one intermediate point along the line by pump light injected into a mixing fiber. According to the invention, the pump light is constituted by two pump waves, the polarizations of the two waves being orthogonal to each other, their optical frequencies being substantially mutually symmetrical about a neutral frequency cancelling the chromatic dispersion of the mixing fiber. The invention is applicable in particular to long-distance links.

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Patents Act

COMPLETE SPECIFICATION
(ORIGINAL)

	Class	Int. Class
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Lodged:		

Complete Specification Lodged:
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Priority

Related Art:

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Invention Title:

AN OPTICAL FIBER TELECOMMUNICATIONS METHOD, A LINK USING THE METHOD, AND A PUMPING SYSTEM FOR FOUR-WAVE MIXING IN PARTICULAR FOR THE LINK

Our Ref : 388880
POF Code: 1501/78784

The following statement is a full description of this invention, including the best method of performing it known to applicant(s):

AN OPTICAL FIBER TELECOMMUNICATIONS METHOD, A LINK USING THE METHOD, AND A PUMPING SYSTEM FOR FOUR-WAVE MIXING IN PARTICULAR FOR THE LINK

The present invention relates to optical fiber telecommunications. It relates more particularly to implementing long-distance links using such fibers for transmitting high data rates.

BACKGROUND OF THE INVENTION

The cost of the fibers required to make up the transmission line of such a link constitutes a large part of the total cost of the link. That is why numerous telecommunications networks use fibers that offer the advantage of being relatively cheap, but that suffer from the drawback of having non-negligible chromatic dispersion at the wavelengths used. Such fibers are referred to below as "standard" fibers. Attempts to increase the data rate or the distance of data transmission at such wavelengths and using such fibers come up against the problem the signals being deformed by dispersion in the fibers. More specifically, at a typical wavelength of 1.55 µm, such deformation limits the transmission of an (NRZ) amplitude-modulated signal to about 90 km at 10 Gbit/s. Therefore, it poses a major problem.

Known solutions to that problem use passive compensation of the dispersion. They lead to very high costs.

Another solution has been proposed by an article entitled COMPENSATION OF FIBRE CHROMATIC DISPERSION BY SPECTRAL INVERSION - R.M. Jopson, A.H. Gnauck and R.M. Derosier - ELECTRONICS LETTERS 1st April 1993 - vol. 29 - No. 7.

That solution consists in inverting the optical phase of a wave carrying the signal midway along the transmission path. For that purpose, a "four-wave mixing" phenomenon is used which produces phase conjugation. More specifically, an incident wave modulated by the signal to be transmitted and referred to below as the "upstream wave" is mixed with a

continuous and powerful pump wave in a mixing fiber. The optical frequency vo of the pump wave, which frequency is referred to below as the "pump frequency", must coincide with a neutral frequency vo which cancels the dispersion of the mixing fiber which, for that purpose, must be of the dispersion-shifted type. Furthermore, the polarization of the pump wave must be linear and parallel to that of the upstream wave. A downstream wave is then generated with phase inverted relative to the upstream wave, and the optical frequency va of the downstream wave is symmetrical to the optical frequency vs of the upstream wave about the neutral frequency vo. Therefore, the downstream wave can be filtered prior to being amplified and prior to propagating along the following line segment which is made up of ordinary fibers.

That solution proves difficult to apply to a practical implementation of an optical link, in particular a long-distance high data rate link. The power of the downstream wave generated in that way varies strongly and quickly. On reception, such power variations prevent the transmitted data from being restored correctly, i.e. they give rise to a high error rate.

OBJECTS AND SUMMARY OF THE INVENTION

Particular objects of the present invention are to make it possible:

to reduce the error rate and/or the cost of an optical fiber link;

to increase the length and/or the data rate of the link;

for that purpose, to compensate more effectively for the effects of the chromatic dispersion of ordinary fibers by means of a four-wave mixing phenomenon generating a downstream wave having phase inverted relative to an upstream wave; and

more generally, to increase the utility of such a phenomenon by freeing the power of the downstream wave from variations which appear when such a method is implemented

under conditions that are far removed from those of a laboratory.

To these ends, the invention provides in particular an optical fiber telecommunications method, in which method light waves carrying a signal to be transmitted are guided along a line made up of optical fibers having chromatic dispersion, and in which method a four-wave mixing phenomenon is caused at at least one intermediate point along the line by pump light injected into a mixing fiber so as to compensate for the effects of the dispersion, wherein the pump light is constituted by two pump waves, the polarizations of the two waves being orthogonal to each other, their optical frequencies being substantially mutually symmetrical about a neutral frequency cancelling the chromatic dispersion of the mixing fiber.

By using the two pump waves, the power of the downstream wave is made independent from the polarization of the upstream wave. In this way, the power of the downstream wave does not vary as a result of variations in the polarization of the upstream wave. Therefore, the invention offers a major advantage in all cases in which the polarization of the upstream wave has random variations. Such is the case in particular at an intermediate point along a long-distance optical link.

BRIEF DESCRIPTION OF THE DRAWING

A more detailed description of how the present invention may be implemented is given below by way of non-limiting example and with reference to the diagrammatic figures of the accompanying drawing. When the same element is shown in more than one figure, it is given the same reference. In the accompanying drawing:

Figure 1 is a view of an optical link of the invention;

Figure 2 shows a light-wave spectrum appearing in a known four-wave mixing assembly; and

Figure 3 shows a light-wave spectrum appearing in a four-wave mixing assembly included in the link shown in Figure 1.

MORE DETAILED DESCRIPTION

The optical fiber link given by way of example includes the following elements:

- A transmitter 1 receiving a signal S representing data to be transmitted. The transmitter responds by transmitting a departure wave W1 constituted by an optical carrier wave which is modulated to carry the signal. The wave has a modulation spectrum SW1 whose width LM is representative of the data rate of the signal. Typically, the polarization of the wave is linear.

- An optical line L having an input 2 for receiving the departure wave, and an output 3 remote from the input for responding by restoring an arrival wave W2 which is formed from the departure wave so that it also carries the signal S.

- A receiver 4 receiving the arrival wave W2 for responding by restoring the signal S.

The line L has a succession of segments T1, 8, T2 optically connected together in series between the input 2 and the output 3, and constituted by optical fibers of the line. The fibers are capable of guiding waves whose optical frequencies lie in a spectral range DS of the line, the range including the frequencies νs and νa of the departure wave and of the arrival wave. The succession of segments includes an upstream dispersive segment T1 and a downstream dispersive segment T2, in which segments the optical fibers of the line are standard fibers. The fibers are such that the two segments have same-sign chromatic dispersions in the spectral range of the line. The dispersions give rise to progressive offsets between various spectrum components of the waves that are guided by the line. The dispersions also cause the signal restored at the output of the line to have dispersion degradations which must be at least limited so as to limit the error rate of the transmission.

For that purpose, the line further includes at least one mixing assembly 6 interposed optically in series between the upstream dispersive segment T1 and the downstream

dispersive segment T2. The assembly itself includes a mixing segment 8 typically constituted by a mixing fiber having zero chromatic dispersion for a neutral frequency vo situated in the spectral range of the line. An input 10 of the mixing segment receives an upstream wave W1 which is a light wave formed from the departure wave for carrying the signal S. The upstream wave is supplied at the output of the upstream segment T1 with an upstream carrier frequency vs lying in the spectral range of the line. An output 12 of the mixing segment 8 supplies a downstream wave W2 at an input of the downstream segment T2, which downstream wave has a carrier frequency va lying in the spectral range of the line, and from which downstream wave the arrival wave is to be formed. More particularly, in the link given by way of example, the upstream wave is constituted directly by the departure wave itself, after the departure wave has been subjected to attenuation and amplification accompanied in particular by random variations in its polarization, in an initial fraction of the length of the line, which fraction constitutes the segment T1. Likewise, the arrival wave is constituted directly by the downstream wave after the downstream wave has travelled over a final fraction of the length of the line, which final fraction constitutes segment T2. Since the length of the mixing fiber is very short compared with the total length of the line, each of the two fractions (initial and final) represents substantially half of said total length.

The mixing assembly further includes a pumping system, itself including the following elements:

• A pump generator for supplying pump light spectrally centered in the vicinity of the neutral frequency, which light has power that is sufficient to give rise to non-linear effects in the mixing segment.

• A pump coupler 14 injecting the pump light into the mixing segment 8 in the same direction as the upstream wave W1 at a pump injection point 16. This gives rise t the four-wave mixing phenomen n. This phen men n generates the

downstream wave W2 with a carrier frequency νa and a modulation spectrum SW2 that are symmetrical to the carrier frequency νs and to the modulation spectrum SW1 of the upstream wave W1 about the pumping light. At the same tim , the phenomenon imparts phase conjugation resulting in phase inversion between the downstream wave and the upstream wav .

• A mixing output filter 18 for transmitting the downstream wave only.

In a known four-wave mixing assembly implemented under laboratory conditions, the upstream wave has a controlled constant direction linear polarization. The pumping light is then chosen to have an optical frequency equal to the neutral frequency νo of the mixing fiber and a linear polarization parallel to that of the upstream wave.

According to the present invention, the pump generator includes two pump sources G1, G2 supplying the pumping light in the form of two pump waves having respective optical frequencies νP1, νP2 that are symmetrical about a middle pump frequency νo. The middle frequency is equal to, or at least in the vicinity of, the neutral frequency νo of the mixing segment 8. The two pump waves also have respective orthogonal linear polarizations V1, V2. The pump coupler 14 injects the two pump waves together into the mixing segment 8. Under these conditions, the power of the downstream wave W2 generated by the four-wave mixing phenomenon becomes independent from the polarization of the upstream wave W1 at the pump injection point 16.

More precisely, the middle pump frequency must be such that, at any point along its length, the mixing segment has two chromatic dispersions that are equal in absolute terms and that have opposite signs for two frequencies that are symmetrical to each other about the middle frequency, one of the two frequencies being the carrier frequency of the upstream wave, and the other frequency being the carrier frequency of the downstream wave.

Typically, the chromatic dispersi n of kn wn optical fibers varies lin arly as a functi n of ptical frequency so

that the above condition stating that the two chromatic dispersions must be opposite for two frequencies that are symmetrical about the middle pump frequency is equivalent to a simpler condition stating that the middle pump frequency must be equal to the neutral frequency of the mixing fiber.

To prevent the signal being degraded by intermodulation products, the two pump frequencies vP1, vP2 have a difference vP1 - vP2 that is greater than the width LM of the modulation spectrum of the departure wave.

Preferably, the two pump waves P1, P2 have substantially the same power (K). Regardless of whether or not they are equal, each of the two powers is preferably greater than 1 mW, e.g. lying in the range 1 mW to 5 mW. The mixing segment preferably has a length greater than 1 km, e.g. about 10 km. Typically, it is constituted by a single optical fiber.

Preferably, the mixing output filter 18 has rejection greater than about 20 dB for the pump waves P1, P2 and the upstream wave W1.

Advantageously, the pumping system includes an optical amplifier 20 for amplifying both the two pump waves P1, P2 and also the upstream wave W1. Typically, the line L includes other amplifiers such as 22. It may further include a plurality of mixing assemblies distributed over its length.

On manufacturing the pumping system for a future optical link, at least one of the two pump sources G1, G2, e.g. single-frequency semiconductor lasers, and the mixing output filter 18, e.g. of the Fabry-Perot type, are chosen to be tunable. Such tunability enables in particular the middle pump frequency no to be subsequently made equal to the neutral frequency of a mixing fiber 8 (once the neutral frequency has been defined).

In the above-described example, the pump frequencies vP1, vP2 lie in the range delimited by the upstream carrier frequency vs and the downstream carrier frequency va, i.e. the difference vP2 - vP1 between the pump frequencies is

less than the difference $\nu a - \nu s$ between the carrier frequencies. However, it is to be understood that the difference $\nu P2 - \nu P1$ could be greater than $\nu a - \nu s$.

XXXXXX The claims defining the invention are as follows:

1/ An optical fiber telecommunications method, in which method light waves carrying a signal to be transmitted are guided along a line made up of optical fibers having chromatic dispersion, and in which method a four-wave mixing phenomenon is caused at at least one intermediate point along the line by pump light injected into a mixing fiber so as to compensate for the effects of the dispersion, wherein the pump light is constituted by two pump waves, the polarizations of the two waves being orthogonal to each other, their optical frequencies being substantially mutually symmetrical about a neutral frequency cancelling the chromatic dispersion of the mixing fiber.

2/ An optical fiber link including:

a transmitter receiving a signal representing data to be transmitted, the transmitter responding by transmitting a departure wave constituted by an optical carrier wave which is modulated to carry the signal, so that the wave has a modulation spectrum whose width is representative of the data rate of the signal;

an optical line having an input for receiving said departure wave, and an output remote from the input for responding by restoring an arrival wave formed from the departure wave so that it also carries the signal, and

a receiver receiving the arrival wave for responding by restoring the signal;

said line having a succession of segments optically connected together in series between said input and said output, and constituted by optical fibers of the line, the fibers being capable of guiding light waves whose optical frequencies lie in a spectral range of the line, the range including the optical frequencies of the departure wave and of the arrival wave, the succession including an upstream dispersive segment and a downstream dispersive segment, in which segments said optical fibers of the line are standard fibers so that the two segments have same-sign chromatic

dispersions in the spectral range of the line, which dispersions give rise to progressive offsets between various spectrum components of waves guided by the line, so that th signal restored at the output of the line may have dispersion degradations due to the dispersions, which dispersion degradations must be at least limited, the line further including, for that purpose, at least one mixing assembly interposed optically in series between said upstream dispersive segment and said downstream dispersiv segment, and itself including:

one of said segments constituting a mixing segment and having zero chromatic dispersion for a neutral frequency situated in the spectral range of the line, an input of the mixing segment receiving an upstream wave which is a light wave formed from said departure wave for carrying the signal, and which is supplied at the output of said upstream segment with an upstream carrier frequency lying in the spectral range of the line, an output of the mixing segment supplying a downstream wave at an input of said downstream segment, which downstream wave has a carrier frequency lying in the spectral range of the line, and from which downstream wave said arrival wave is to be formed; and

a pumping system, itself including:

a pump generator for supplying pump light spectrally centered in the vicinity of said neutral frequency, which light has power that is sufficient to give rise to non-linear effects in the mixing segment;

a pump coupler for injecting the pump light into the mixing segment in the same direction as the upstream wave at a pump injection point so as to give rise to a four-wave mixing phenomenon which generates the downstream wave with a carrier frequency and a modulation spectrum that are symmetrical to the carrier frequency and to the modulation spectrum of the upstream wave about the pumping light, and with phase conjugation resulting in phase inversion between the downstream wav and the upstream wave; and

a mixing output filter for transmitting the downstream wave only;

wherein the pump generator includes two pump sources supplying the pumping light in the form of two pump waves having respective optical frequencies that are symmetrical about a middle pump frequency, the middle frequency being at least in the vicinity of the neutral frequency of the mixing segment, the two pump waves also having respective orthogonal linear polarizations, the pump coupler injecting the two pump waves into the mixing segment, thereby causing the downstream wave generated by the four-wave mixing phenomenon to have power that is independent from the polarization of the upstream wave at the pump injection point.

3/ A link according to claim 2, wherein the two pump frequencies have a difference that is greater than the width of the modulation spectrum of the departure wave.

4/ A link according to claim 2, wherein the two pump waves have substantially the same power.

5/ A link according to claim 2, wherein each of the two pump waves has power greater than 1 mW, e.g. lying in the range 1 mW to 5 mW, the mixing segment having a length greater than 1 km.

6/ A link according to claim 2, wherein the mixing output filter has rejection greater than about 20 dB for the pump waves and the upstream wave.

7/ A link according to claim 2, wherein the pumping system further includes an optical amplifier for amplifying both the two pump waves and also the upstream wave.

8/ A pumping system for four-wave mixing, wherein it is a system according to the pumping system of claim 2.

9/ A pumping system according to claim 8, wherein at least one of the two pump sources and the mixing output filter are tunable.

DATED: 3rd November, 1994

PHILLIPS ORMONDE & FITZPATRICK

Attorneys for: David B Fitzpatrick

ALCATEL N.V.

ABSTRACT

Light waves carrying a signal to be transmitted are guided along a line made up of optical fibers having chromatic dispersion. To compensate for the effects of the dispersion, a four-wave mixing phenomenon is caused at at least one intermediate point along the line by pump light injected into a mixing fiber. According to the invention, the pump light is constituted by two pump waves, the polarizations of the two waves being orthogonal to each other, their optical frequencies being substantially mutually symmetrical about a neutral frequency cancelling the chromatic dispersion of the mixing fiber. The invention is applicable in particular to long-distance links.

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FIG.1

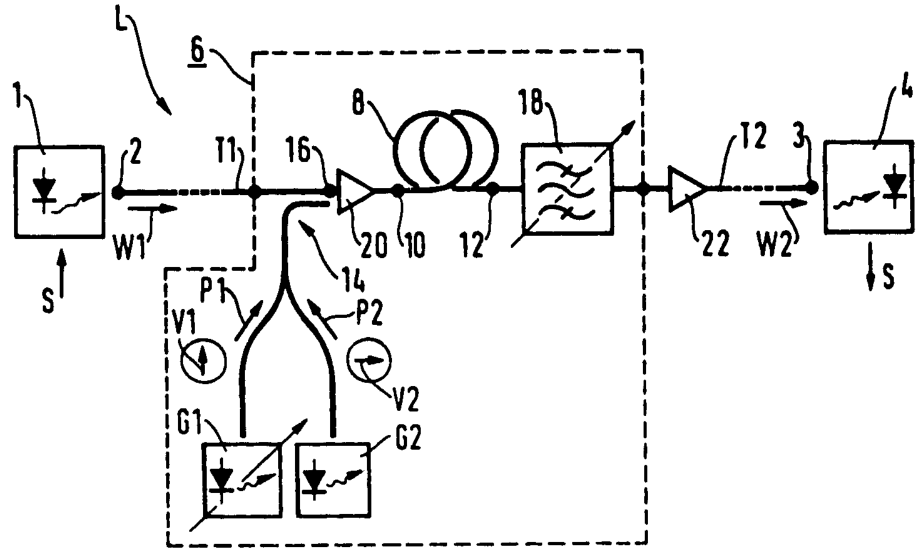

FIG.2

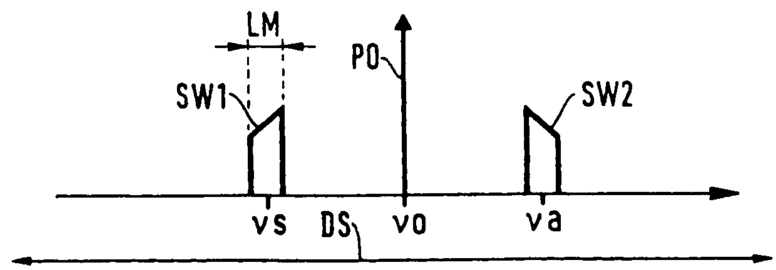

FIG.3